Prospects for the first W mass measurement @ LHC

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On behalf of the CMS and ATLAS Collaborations

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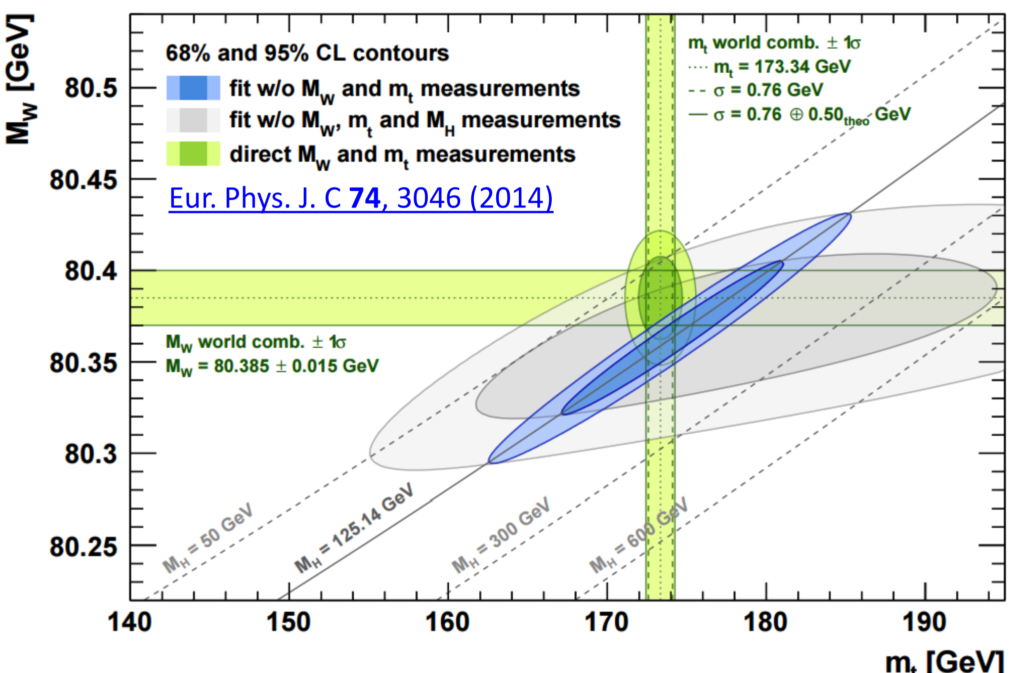
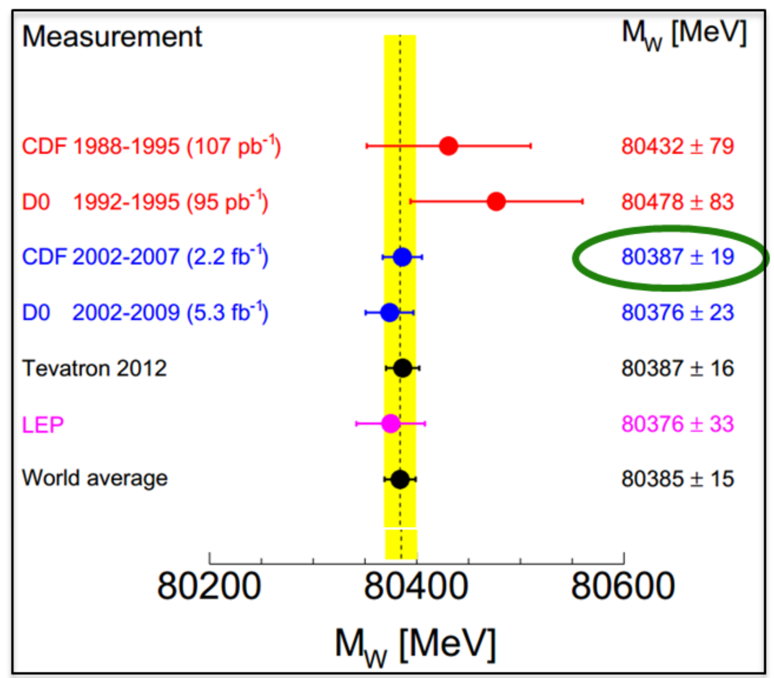
Motivations

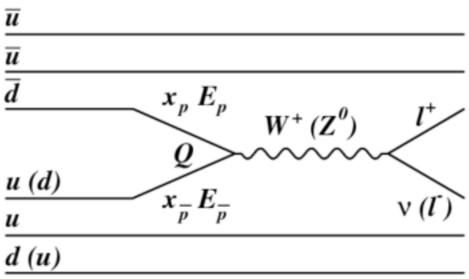
- A precise measurement of M_W provides a crucial test of the SM
- The EWK gauge sector of the SM is mainly constrained by three parameters
  - $\alpha_{EM}(M_Z)$, G_F, M_Z = 91.1876 (21) GeV
- Related to M_W at tree-level, via $M_W^2 = \pi\alpha_{EM} / \sqrt{2}G_F\sin^2\vartheta_W$ where $\cos\vartheta_W = M_W/M_Z$
  - Top and W boson mass (over)constrain the mass of the Higgs boson, and possibly new particles beyond the standard model
    - SUSY particles can contribute O(100) MeV to M_W via loop corrections
    - Progress on ΔM_W has the biggest impact on the SM fit (need to target < 10 MeV uncertainty)



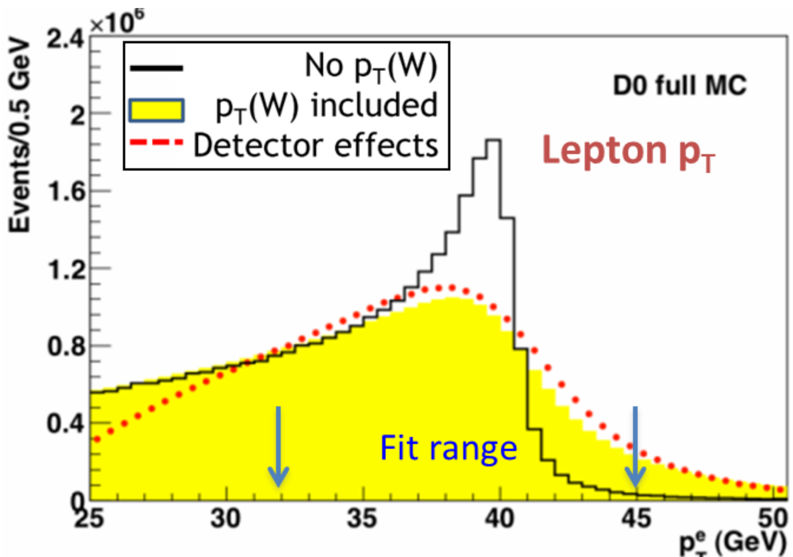


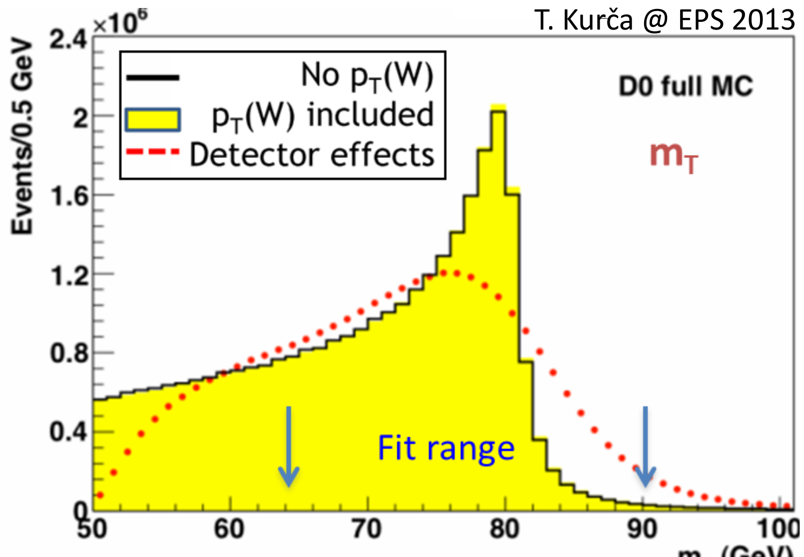
Measurement strategy

- W production is abundant at hadron colliders
  - O(100M) leptonic W events in LHC Run 1 (stat uncertainty << 5 MeV)
- Measurement requires control of several aspects
  - Theoretical: PDF, QCD (boson pT, polarization), QED (FSR)
  - Experimental: lepton momentum scale, hadronic recoil resolution
- Template analysis: compare DATA/MC for transverse observables
  - Muon p_T → most affected by pT(W) uncertainties
  - Missing E_T → most affected by detector resolution effects
  - m_T → best compromise between TH and EXP (cfr de Rujula et al, arXiv:1106.0396)
- At low boson pT : $m_T \sim 2p_T^{\mu} + p_T^{W}$
- To get 10 MeV on m_W: 10^{-4} precision on p_T^{μ} (~40 GeV) and 10^{-3} on p_T^{W} (~5 GeV)



T. Kurča @ EPS 2013



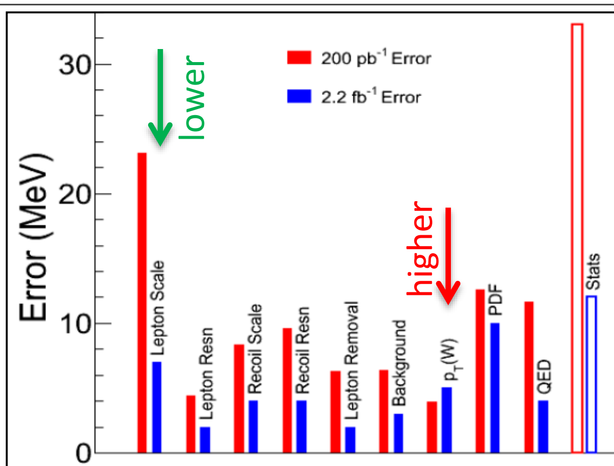


Pre~~v~~cious measurements: Tevatron

- W mass uncertainties can be factorized into 2 distinct parts
  - Experimental systematics (decrease with statistics)
  - Theory systematics (do not decrease with statistics)

CDF

Source	Uncertainty
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton tower removal	2
Backgrounds	3
PDFs	10
$p_T(W)$ model	5
Photon radiation	4
Statistical	12
Total (combination)	19



D0

Source	Public. 2009 (1.0 fb^{-1})	Public. 2012 (4.3 fb^{-1})
Statistical	23	13
Experimental syst.		
Electron energy scale	34	16
Electron energy resolution	2	2
EM shower model	4	4
Electron energy loss	4	4
Hadronic recoil	6	5
Electron ID efficiency	5	1
Backgrounds	2	2
Subtotal experimental syst.	35	18
***W* production and decay model**		
PDF	9	11
QED	7	7
boson p_T	2	2
Subtotal W model	12	13
Total systematic uncert.	37	22
Total	**44**	**26**

Electron energy scale: 34 → 16 (lower); PDF: 9 → 11 (higher)

combination: 23

CDF, PRD 89 (2014) 072003, arXiv:1203.0275v1 [hep-ex], 2.2 fb^{-1}

D0, PRD 89 (2014) 012005 , arXiv:1310.8628v2 [hep-ex], 4.3 fb^{-1}

Towards the W mass @ LHC

- Measurement sitting on the shoulder of the (Tevatron) giants

- **Statistical precision 7 TeV data (~4.5 fb^{-1}): < 10 MeV / channel**
  - Extrapolating: 8 TeV data (~20 fb -1): < 5 MeV / channel
  - Each experiment can reach << 5 MeV statistical precision with Run 1

- Challenges at the LHC:
  - Higher pile-up environment $\rightarrow$ affect hadronic recoil resolution and calibration
  - Different energy regime 2 TeV vs 7/8/13 TeV, p-p instead of p-p collisions, potentially larger theoretical uncertainties
  - W^+ and W^- production is not symmetric $\rightarrow$ Charge-dependent analysis
- Advantages:
  - Large calibration samples: 1-2M (@7 TeV) of Z $\rightarrow$ μμ/ee
  - Large pseudorapidty coverage
  - MC template built with detector full simulation with latest and greatest overall calibration conditions and detector description

The experimental challenges

More data = higher precision

Interlude: the W-like (Z) mass @ CMS

- Z mass measurement in "W like" $Z \rightarrow \mu\mu$ events
  - central "tag muon" $|\eta|<0.9$, other muon removed, MET and m_T recomputed
  - low background
  - use dilepton system to constrain the theory part
- Proof of principle intermediate step
  - Validate tools and techniques to be used in W mass measurement
  - Lead to the improvements in the modeling of W production
  - Statistical uncertainty ~Tevatron level
- Split the sample: half for calibration, half for the measurement
- Caveat: additional systematics need to be accounted for the W mass measurements
  - PDFs in W production
  - $Z \rightarrow W$ extrapolation
  - Background

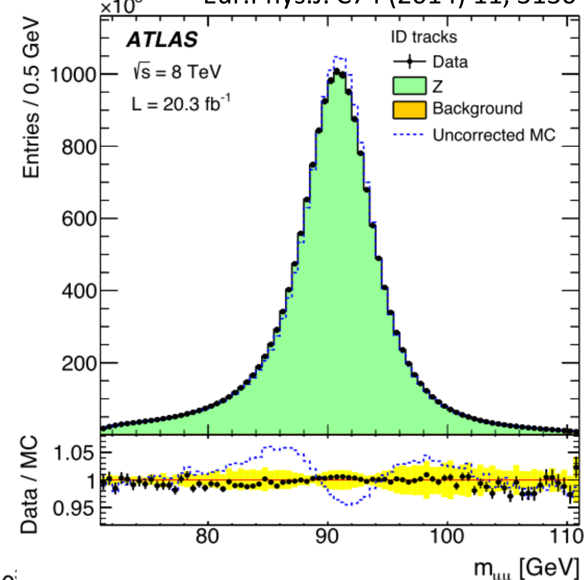
CMS PAS SMP-14-007

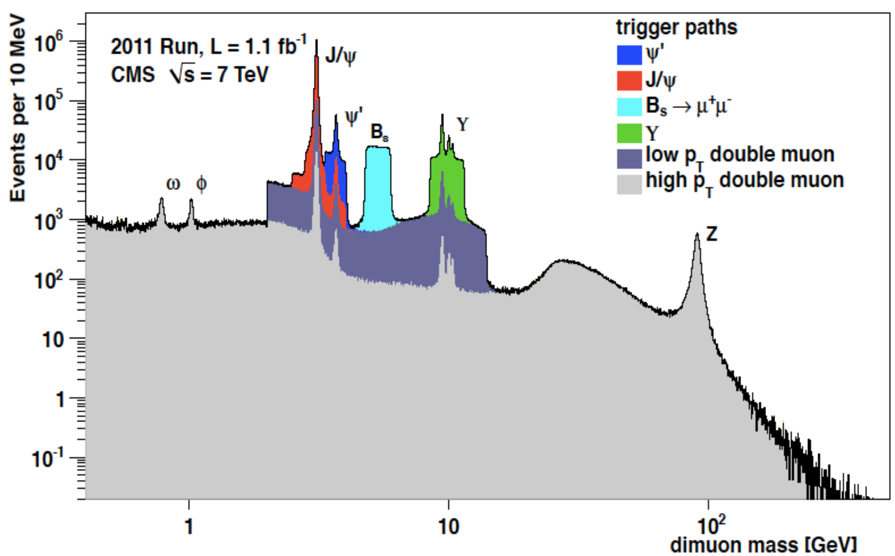
Systematic source	W-like	W
PDF	skip	✓ YES
Boson PT	skip	✓ YES
Boson PT W/Z extrapolation	**NO**	✓ YES
EWK correction	skip	✓ YES
Polarization	skip	✓ YES
μ momentum scale	✓ YES	✓ YES
μ tr-iso-id efficiency	✓ YES	✓ YES
Missing et scale/resolution DATA/MC agreement	✓ YES	✓ YES
MET W/Z extrapolation	**NO**	✓ YES
Background to 1 lepton	**NO**	✓ YES

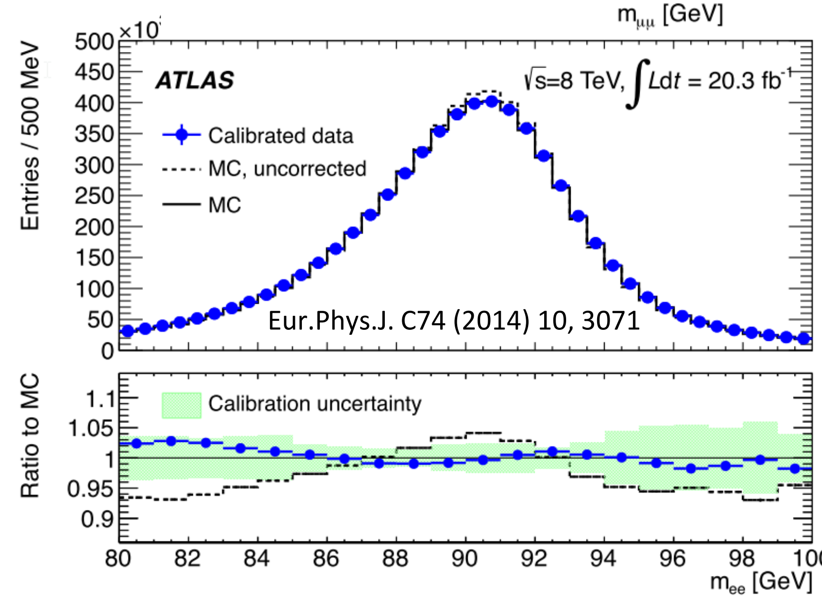
Lepton momentum calibration

- Bottom line: use resonances (J/ψ, Υ, Z)
- For low boson p_T W: $m_T \sim 2p_T^{\mu} + p_T^{W}$
  - To get 10 MeV on m_W: 10^{-4} precision required on p_T^{μ} scale (~40 GeV)
  - Resolution less crucial

Eur.Phys.J. C74 (2014) 11, 3130







Lepton momentum calibration in CMS

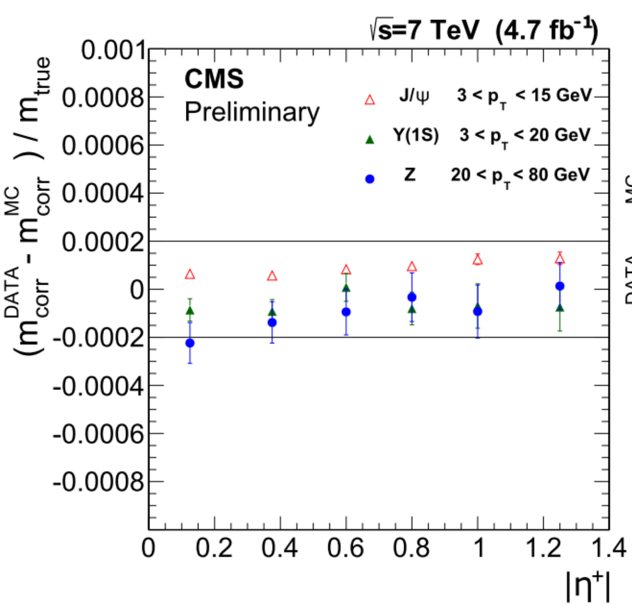
CMS PAS SMP-14-007

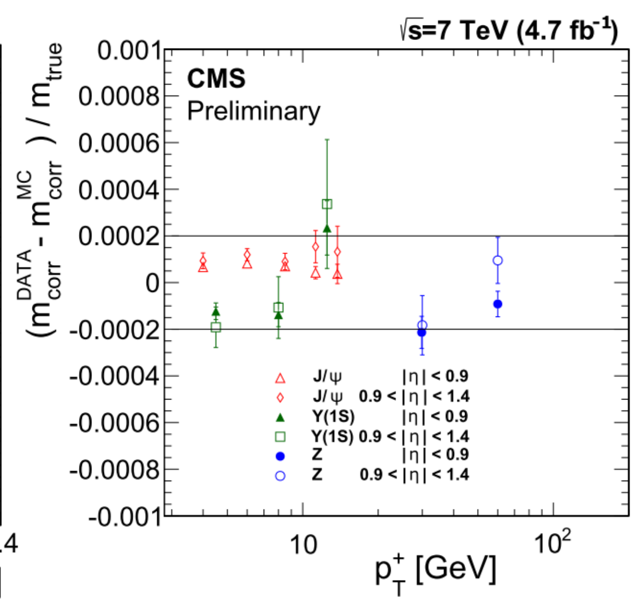
- Calibrate muon curvature (1/pT) using J/ψ, Υ at 7 TeV
- Use a physically motivated calibration model to cover the whole p_T spectrum

$$k^c = (A-1)k + qM + \frac{k}{1 + k\,\epsilon \sin\theta}$$

magnetic field — misalignment — material

- Scale corrections are derived for both Data and simulation
  - Resolution corrections included, accounting for multiple scattering and single hit resolution





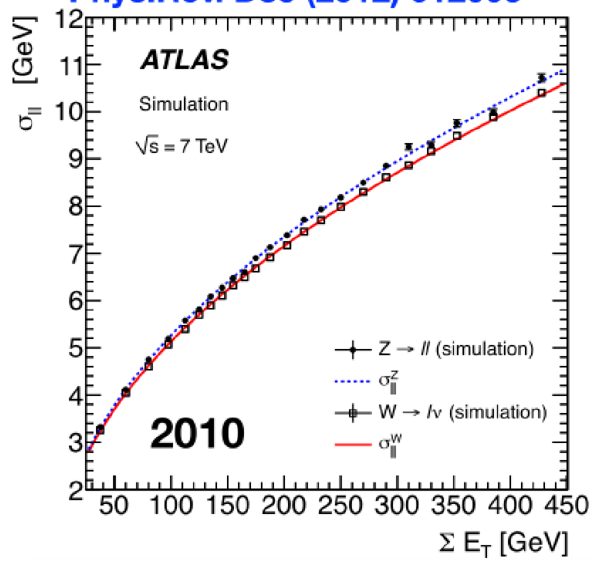
Main uncertainties:

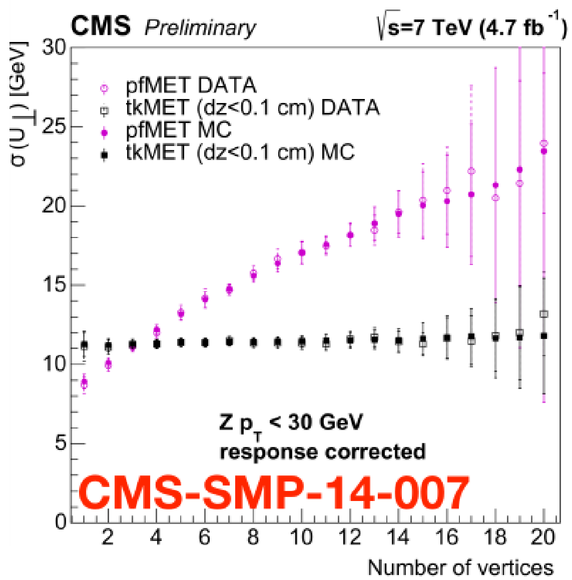
- High mass (J/ψ, Υ to Z) extrapolation
- Statistical power of the calibration sample

Recoil reconstruction

- **Hadronic activity balancing boson p_T + UE, MPI, pileup**
- **ATLAS:** dedicated recoil algorithm for W, Z measurements
  - Sum over calorimeter cells excluding the cells associated to the lepton.
- **CMS:** Particle flow algorithm (pfMET)
  - reconstruction and identification of each particle with an optimized combination of all subdetector information
- Similar resolution between ATLAS and CMS
- CMS improvement: **tkMET**
  - vectorial sum of the pf charged hadron with dz<0.1 cm
    - 80% efficiency for charged tracks p_T>300 MeV, |η|<2.4
  - Suppress in-time pileup at reconstruction level not considering pf hadrons/clusters associated to vertices other than the Primary Vertex
  - Also for high pileup 8 TeV sample
- Better sensitivity (resolution) wrt pfMET in W(-like) events

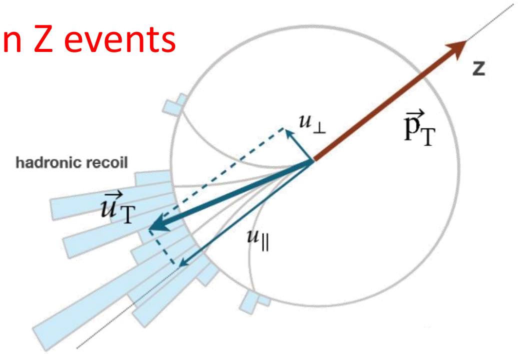
Phys.Rev. D85 (2012) 012005



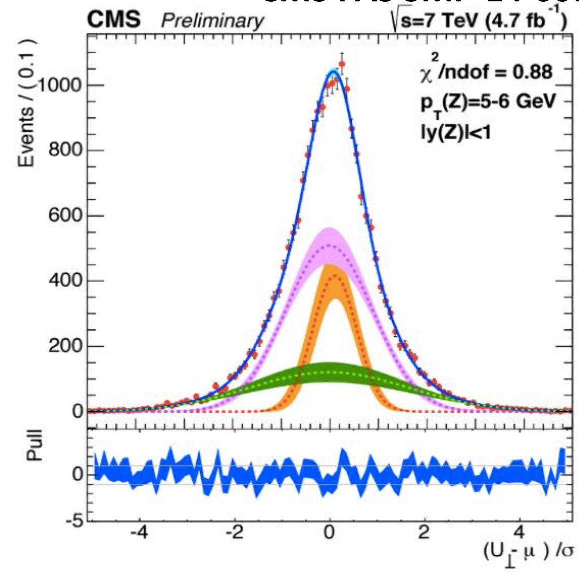


Recoil calibration

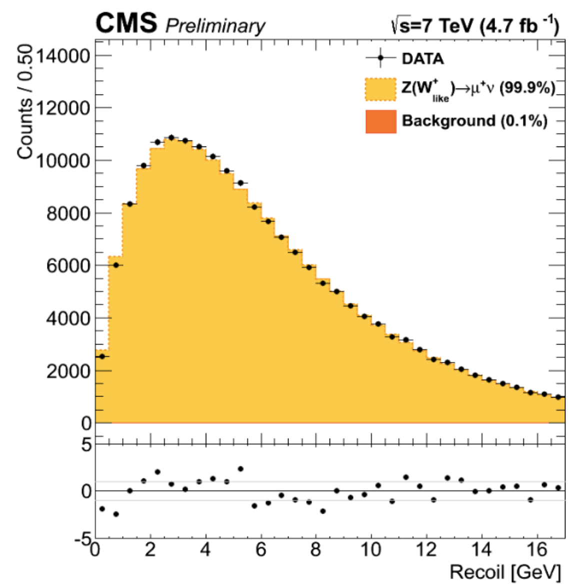
- Different effects: pileup, UE, soft/hard radiations
  - effective calibration based on Z events
- Useful projections: $u_{\perp}$, $u_{\parallel}$: projections of u on axis perpendicular/parallel to boson p_T
- Use to compare recoil resolution and response in data and MC



CMS PAS SMP-14-007



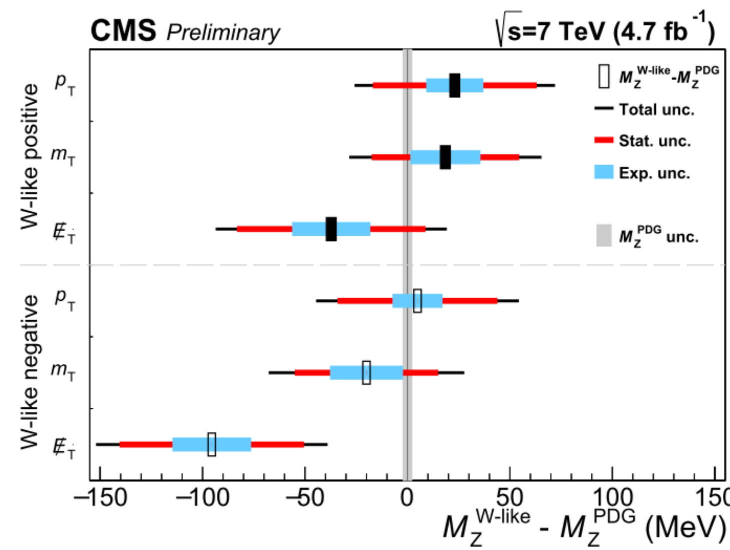
- **CMS** calibration example in the W-like measurement
  - 2D model with sum of 3 Gaussians vs boson p_T
  - Derive corrections, apply them to simulation
  - Correction derived in boson rapidity bins to account for data/simulation discrepancies
- Main uncertainties:
  - Limited statistics of the calibration samples
  - Calibration model (alternative based on adaptive kernel)

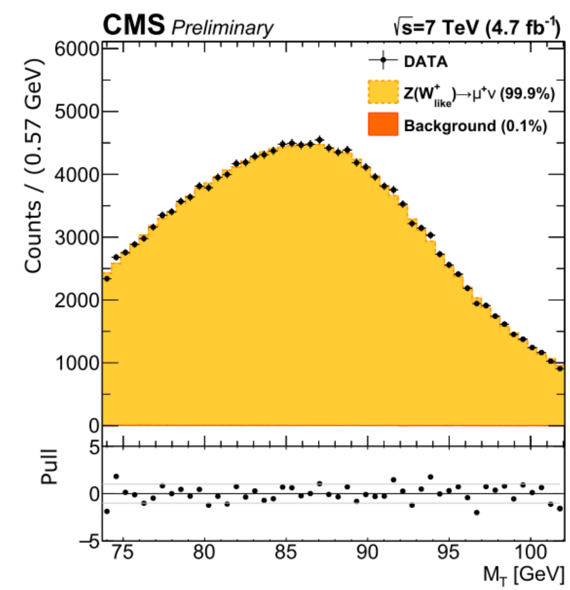


W-like (Z) mass analysis results

Sources of uncertainty	$M_Z^{\mathrm{W\,like}+}$ p_T	m_T	$\not{E}_T$	$M_Z^{\mathrm{W\,like}-}$ p_T	m_T	$\not{E}_T$
Lepton efficiencies	1	1	1	1	1	1
Lepton calibration	14	13	14	12	15	14
Recoil calibration	0	9	13	0	9	14
Total experimental syst. uncertainties	14	17	19	12	18	19
Alternative data reweightings	5	4	5	14	11	11
PDF uncertainties	6	5	5	6	5	5
QED radiation	22	23	24	23	23	24
Simulated sample size	7	6	8	7	6	8
Total other syst. uncertainties	24	25	27	28	27	28
Total systematic uncertainties	28	30	32	30	32	34
Statistics of the data sample	40	36	46	39	35	45
Total stat.+syst.	49	47	56	50	48	57

CMS PAS SMP-14-007





- Experimental uncertainty ~20 MeV (muon channel)
  - Competitive to Tevatron
  - Electron uncertainty uncorrelated, large gain in sensitivity and valuable cross-check
- "Theoretical" uncertainty ~30 MeV
  - Don't translate directly to W mass, also Z→W extrapolation (eg recoil calibration) not accounted for
- PDF likely to be larger for W (for Z constrained by p_T and rapidity meas.)
- QED systematics: on/off NLO EW correction in Powheg-EW (very conservative)

The theoretical challenges

Where are the uncertainties lying?

PDF effects

- PDF uncertainties on m_w dominated by the valence/sea ratio and 2nd generation uncertainties
  - Transverse momentum distribution uncertainties due to uncertainties in the p_T^W
    - Contributions from distribution heavy quark PDFs (+non-perturbative parameters)
- Valence/sea PDF uncertainties
  - Determine the rapidity distribution → acceptance effects
  - Valence PDFs polarize the W decay along z-direction
- At generator level ~10 MeV PDF systematics, but differences between sets 20-30 MeV

arXiv:1501.05587v2

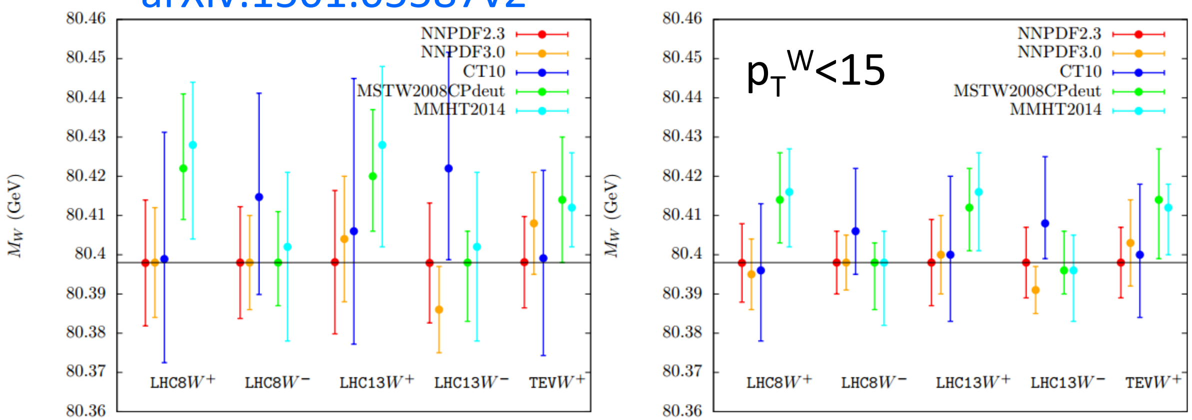


Figure 4: Summary of the PDF uncertainty on m_W computed with different PDF sets, colliders and final states. The basic acceptance criteria have been used in the left plot, while in the right plot an additional cut $p_\perp^W < 15$ GeV has been applied.

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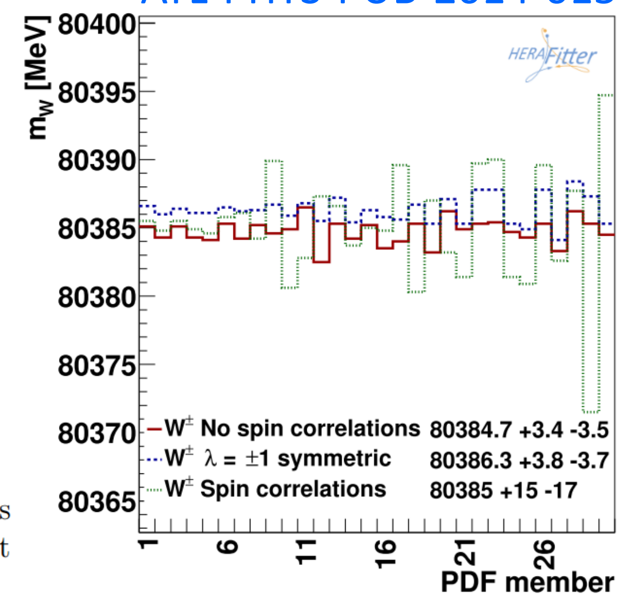
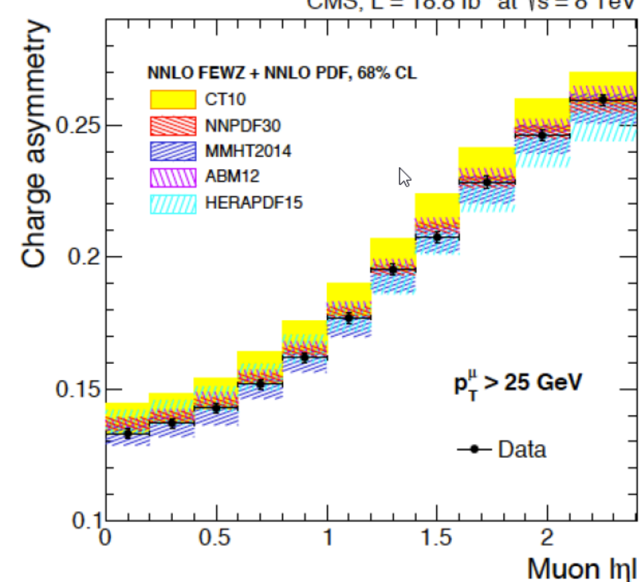


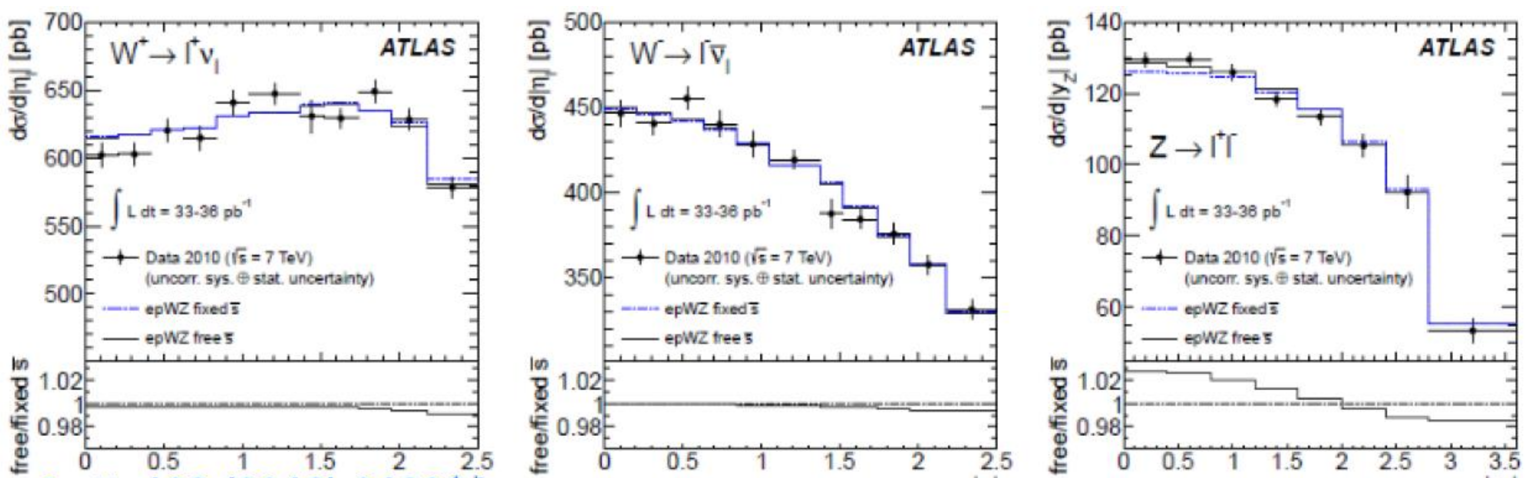
Constraining PDFs

- W charge asymmetry
  - vs rapidity: $A(y) \approx \dfrac{u_V - d_V}{u_V + d_V + 2\, r_s c}$

    where ($r \approx s/d$ and assuming $u \approx d$ and $s \approx s$)
  - most significant improvement in dv
- W and Z cross sections
  - Measured enhancement of Z production at central rapidity is interpreted as enhanced strange density
  - Increasing $s(x)$ (to $r \approx 1$) explains Z data, W unchanged
- W+charm cross section

arXiv:1603.01803v1 [hep-ex]

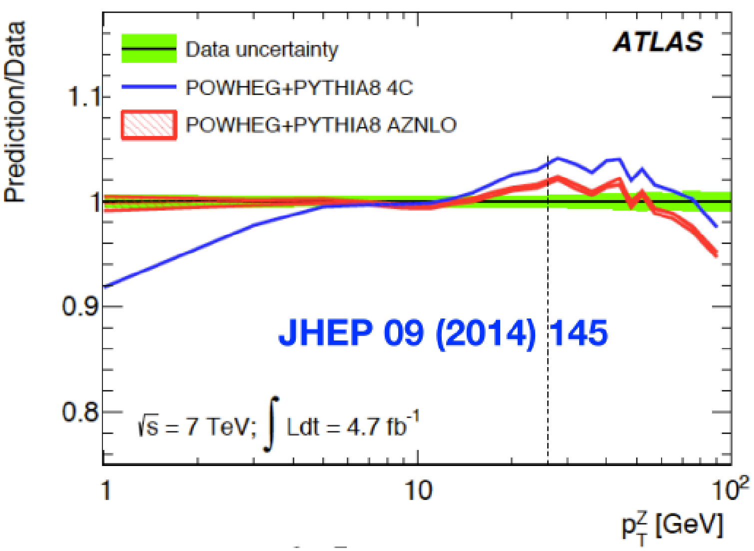


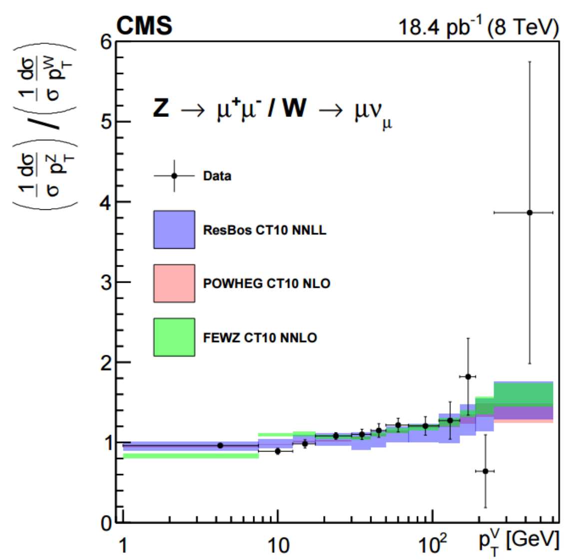


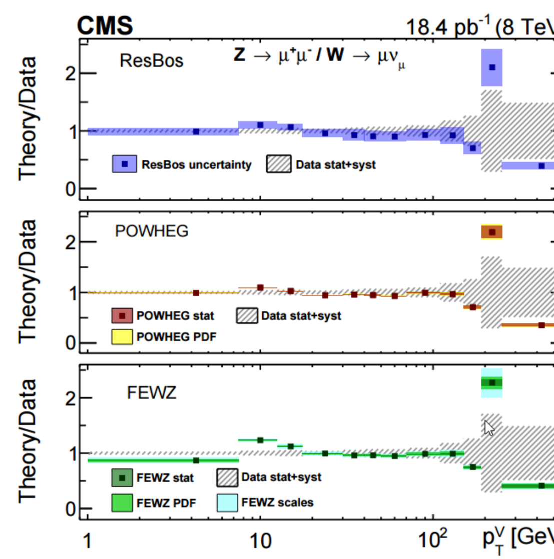
Phys.Rev.Lett. 109 (2012) 012001

p_T^W modeling: learning from p_T^Z

- p_T^Z measurement
  - Measure p_T^Z, tune parton shower (or resummation parameters) then apply to p_T^W
  - Constraints from ATLAS measurement: $\Delta m_W < 5$ MeV assuming no extrapolation uncertainty
  - Caution needed at the LHC: Z , W^+ and W^- have different from 2nd and 3rd generation PDFs (4-8 times larger than Tevatron)
- Modeling of p_T^Z/p_T^W with state of the art generators → interplay with theory community
- Alternative way: direct measurement of p_T^W
  - May need dedicated runs at low pileup ≈250 pb^{-1} at μ≈1, driven by Z statistics (calibration)
  - 2.5% -5% precision reached on p_T^W/p_T^Z (three lowest bins) with the 18.4/pb





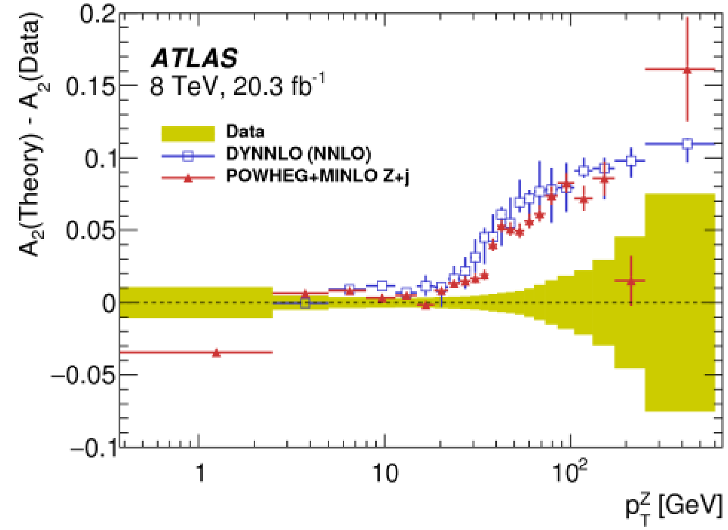


arXiv:1606.05864 submitted to JHEP

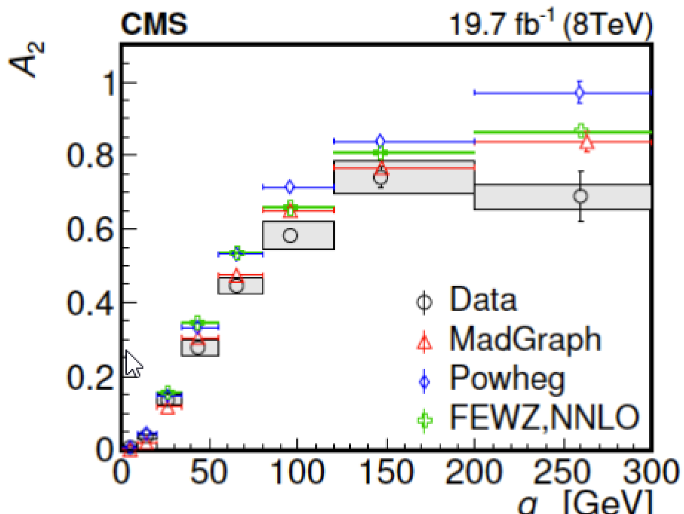
More QCD: angular distributions

arXiv:1606.00689

- The measurements of the correlation of the angular distributions with the lepton transverse momentum distributions, are an important ingredient in M_W measurement
  - **Measured by ATLAS and CMS on Z events**
  - CMS : Comparison of the angular coefficient in the Collin-Soper frame in bins of boson pT and |Y|<1 and |Y|>1
  - ATLAS: in bins of pT and 3 rapidity bins
  - Uncertainty dominated by the PDFs



- Probe QCD corrections beyond the formal accuracy of the calculations.
- Significant deviation from the $O(\alpha_s^2)$ predictions from DYNNLO is observed for A0 – A2 (ATLAS), indicating that higher- order QCD corrections are required to describe the data



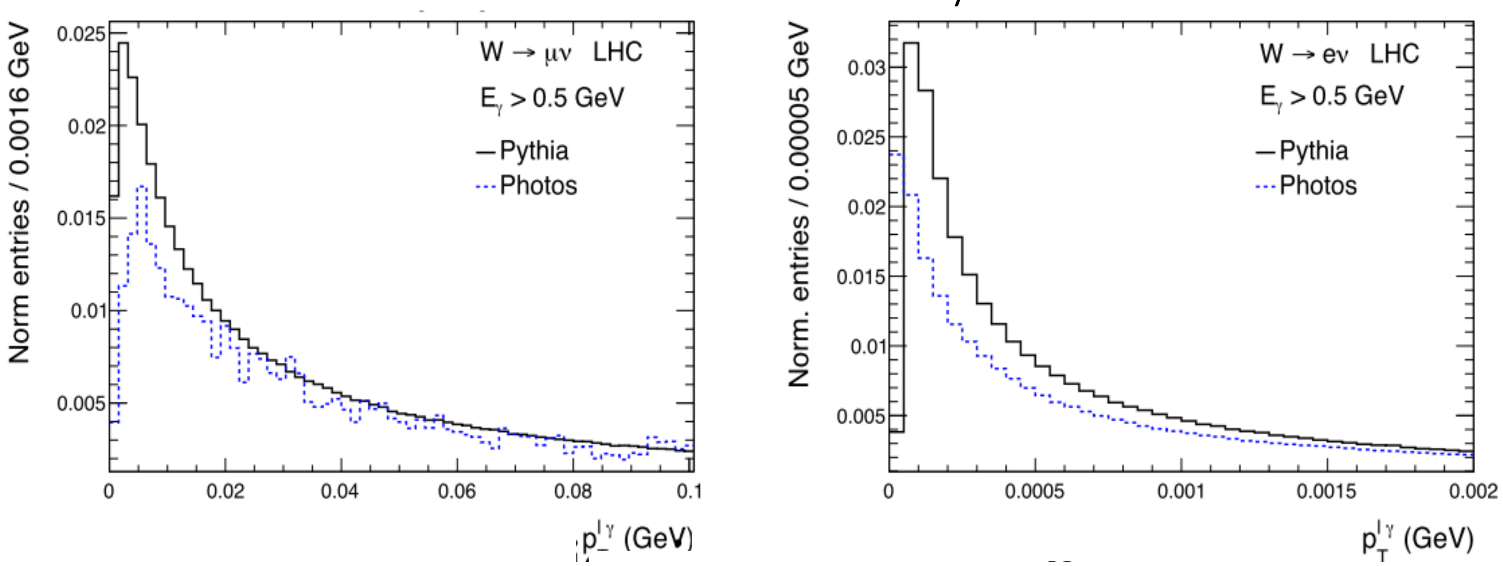
Phys. Let. B 750 (2015) 154

EWK corrections

- Monte Carlo tools usually encode only NLO QCD corrections
- Non-negligible contribution from NLO EWK and cross terms
- Efforts ongoing to consistently include (and validate) both in a single tool for **W** L. Barzé et al, JHEP 1204 (2012) 037 and **Z** L. Barzé et al, Eur.Phys.J. C73 (2013) 2474

- FSR modeling also studied (and understood) in great detail

Courtesy of H. Martinez and collaborators



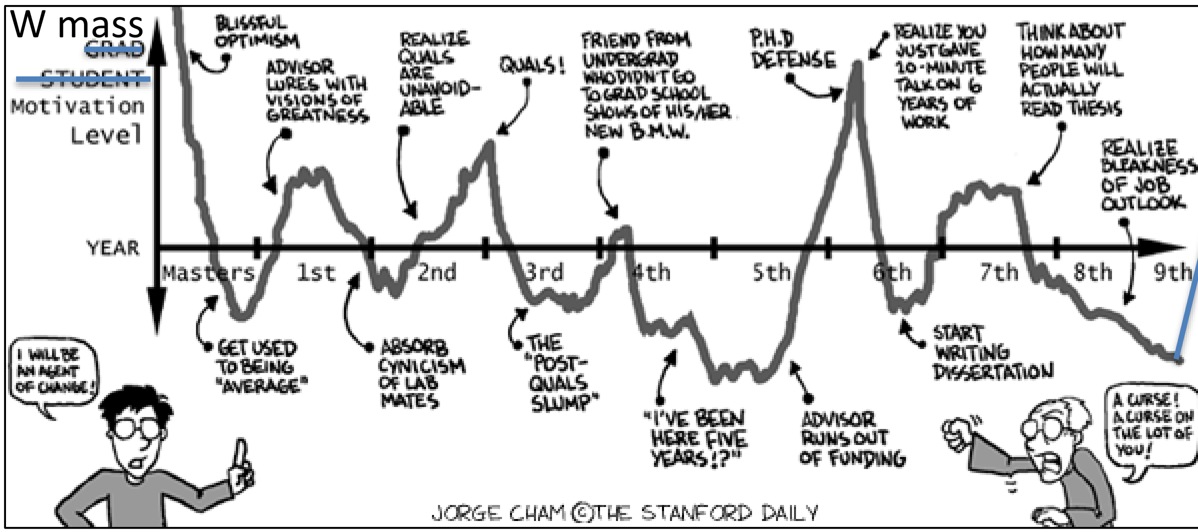
Summary

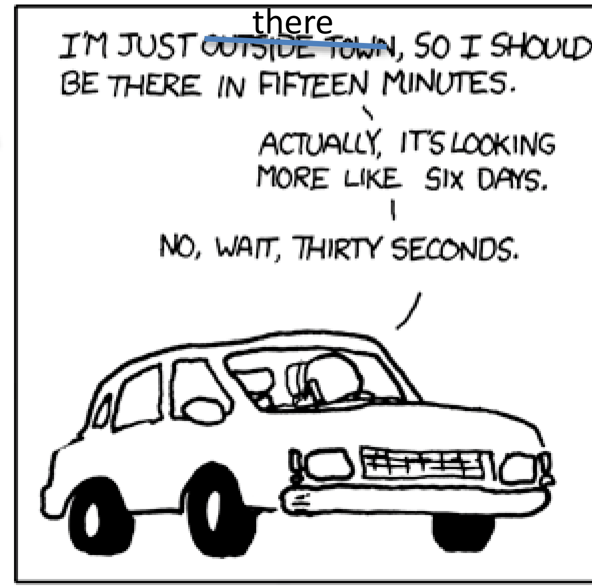
- Long standing effort to measure m_W at the LHC
- Status of experimental systematics seems promising and already comparable to the latest Tevatron results
  - Larger statistics will help in pinning them down further
- Precise assessment of theoretical systematic uncertainties being discussed with the theory community
  - No single tool able to incorporate all the latest and greatest QCD and EWK corrections
  - Non trivial p_T^Z / p_T^W prediction
  - Non trivial interplay between PDF, QCD corrections and parton shower
- New analysis and fitting strategies could help in reducing the impact of syst uncertainties
  - Profiling techniques used in Higgs, featuring in situ constraints with ancillary measurements

Current status

Tevatron	$\delta(\text{stat}) \sim \delta(\text{theo}) \sim \delta(\text{calib})$
LHC	$\delta(\text{theo}) > \delta(\text{calib}) > \delta(\text{stat})$

W mass analysis in a nutshell





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W mass analysis at a conference

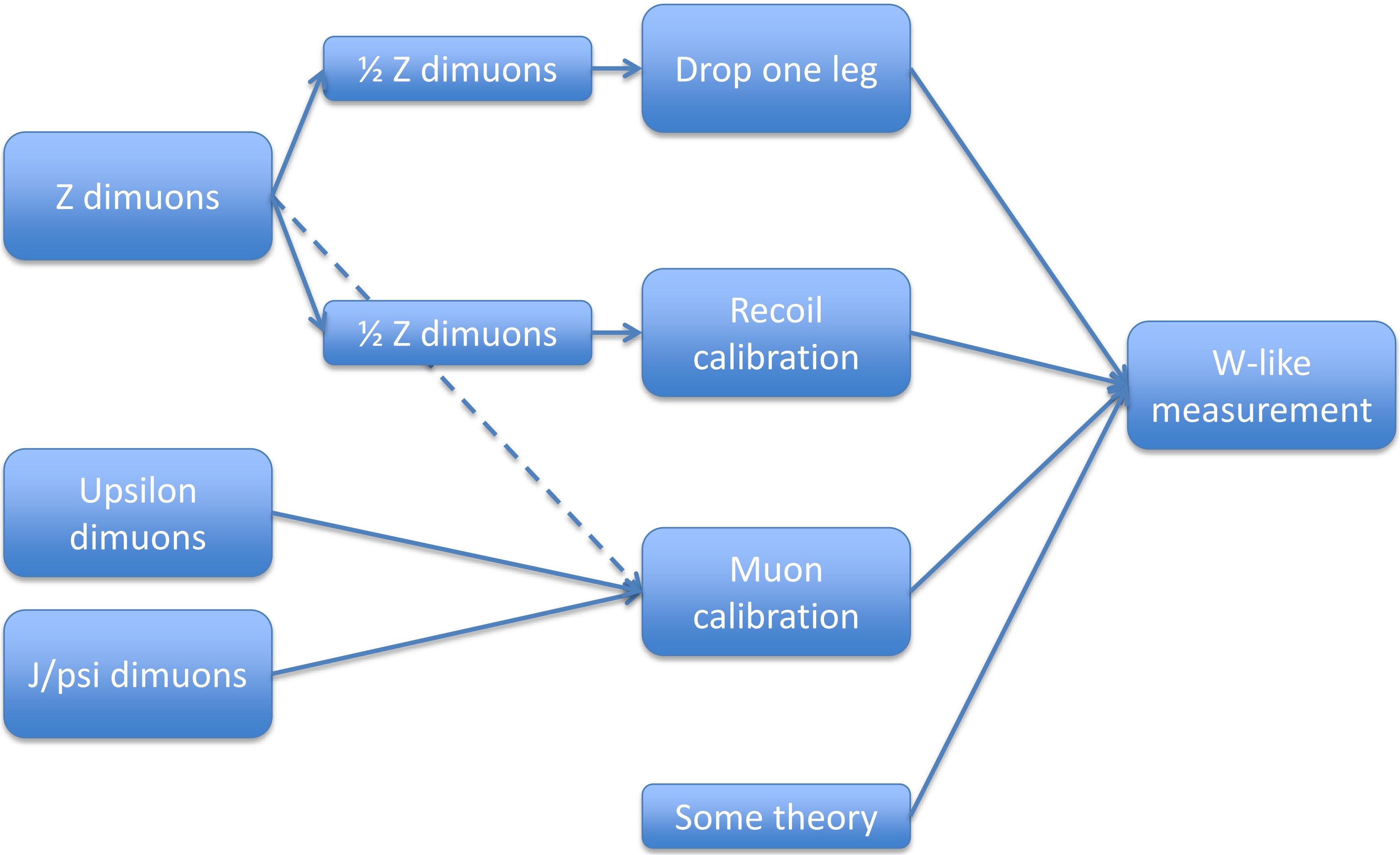
Backup

Further readings and references

Series of workshops to bring together experimentalists and theorists

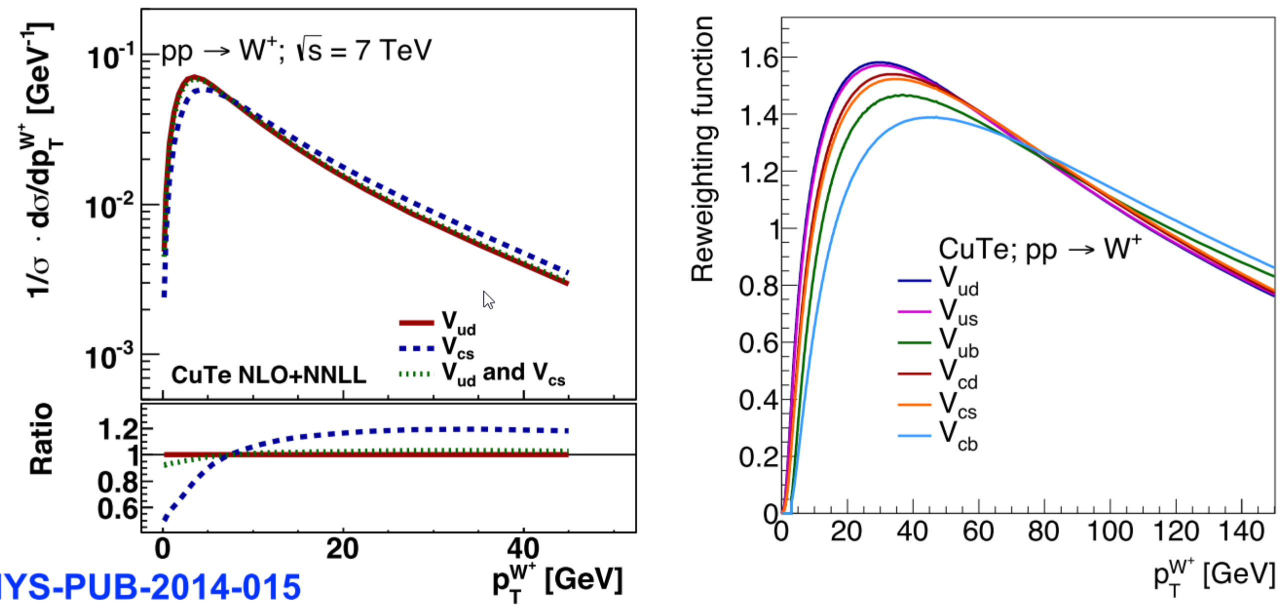
- November 2014 in Florence: https://indico.cern.ch/event/340393/
- February 2015 at CERN: https://indico.cern.ch/event/367442/
- June 2016 at CERN: https://indico.cern.ch/event/367442/
- Next meeting: November 2016 in Mainz

W-like ingredients



PDF and W,Z production

- Main production at LHC : $u\bar{d} \rightarrow W^+$, $du \rightarrow W^-$; $cs \rightarrow W$ ~25%
  - Quark "x" from 10^{-3} to 10^{-1}
- Similar PDFs for W and Z, BUT:
  - charm quark significant to W production (~ (Vcs+Vcd+c.c.), smaller for Z (~ cc)
  - b-quark contributes to Z production (~ bb), negligible to W production (~ (Vcb +c.c.))
- Strange and charm production ~several times lager than in pp in Tevatron
  - Preliminary : 7-9 MeV uncertainty (including experimental effects)



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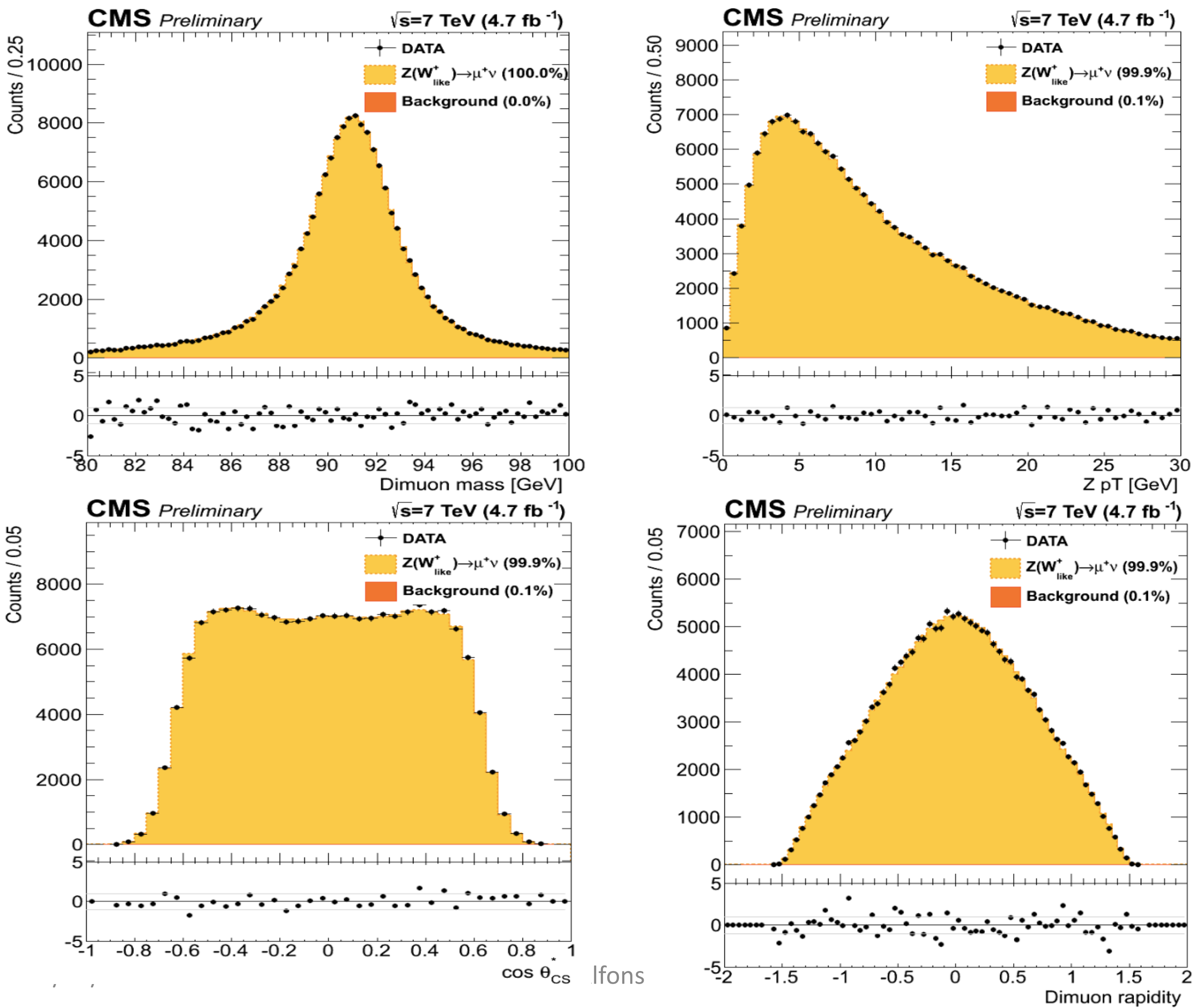
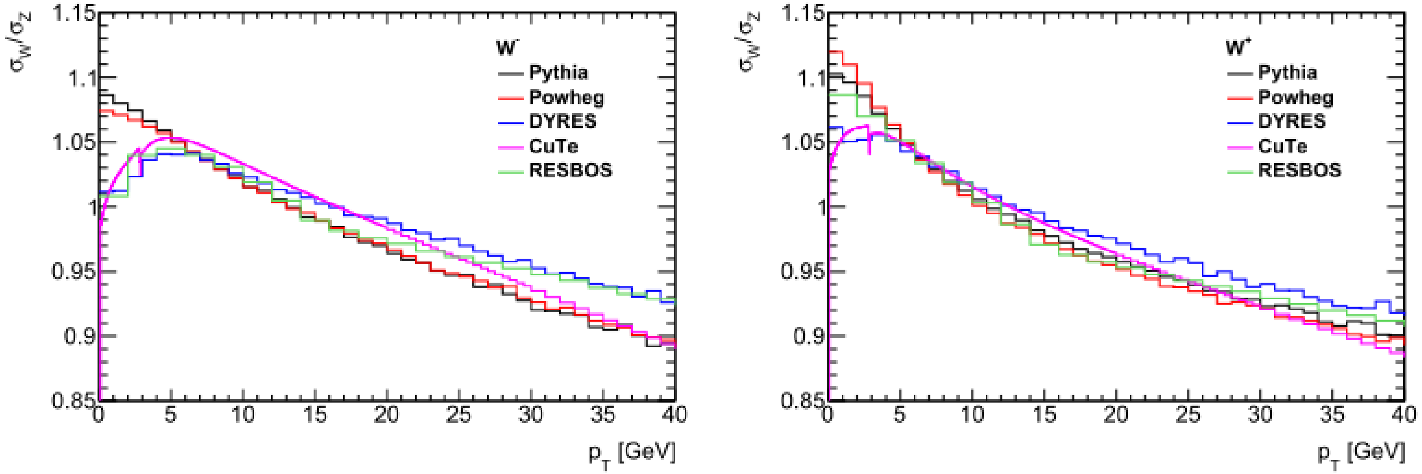
Properties of the W-like system

CMS-SMP-14-007



W/Z p_T predictions

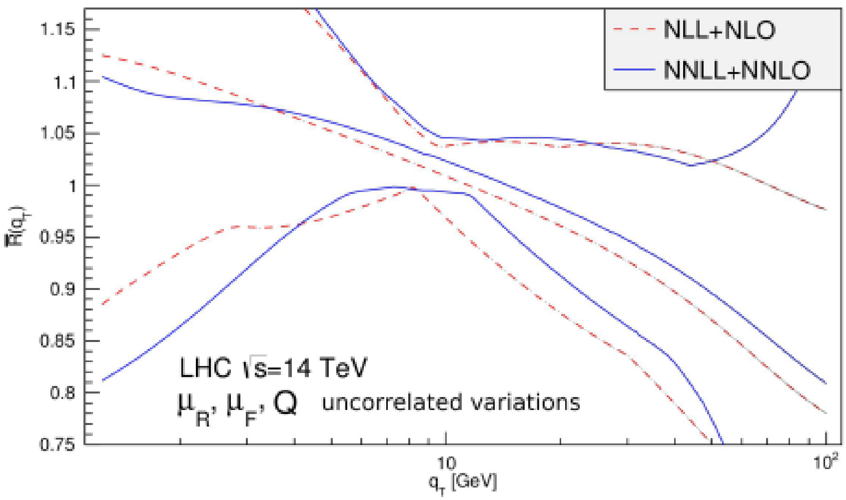
- The strategy of fitting the Z p_T and predicting the W p_T can be applied to any model
- However, different models predict very different W/Z p_T ratios, in particular Pythia8 and Powheg+Pythia8 parton shower models predict a monotonic falling ratio, while predictions based on resummation shows a peak at 5 (3) GeV for W^- (W^+)
- Plots without cuts on the lepton kinematic



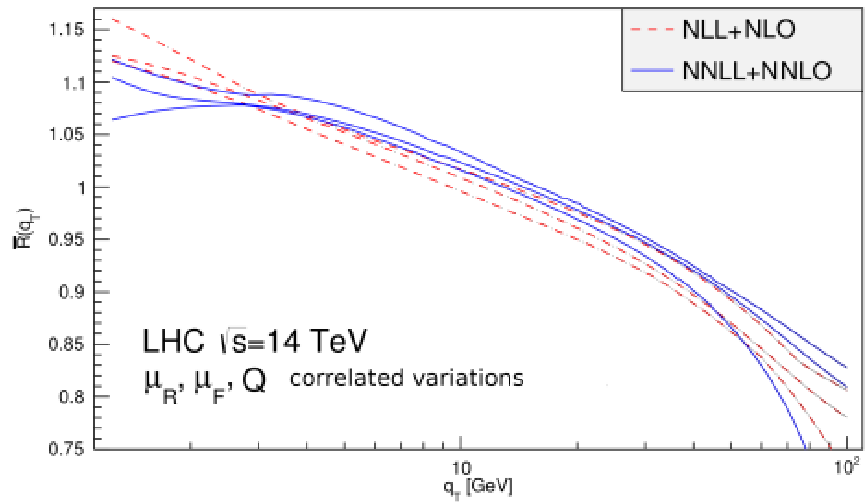
- → Fits to the same Z p_T data of different models can provide very different predictions of the W p_T distribution

W/Z ratio q_T spectrum: perturbative scale uncertainty

In collaboration with L. Talon.



DYqT resummed predictions for the ratio of W/Z normalized q_T spectra. Uncorrelated perturbative scale variation band.



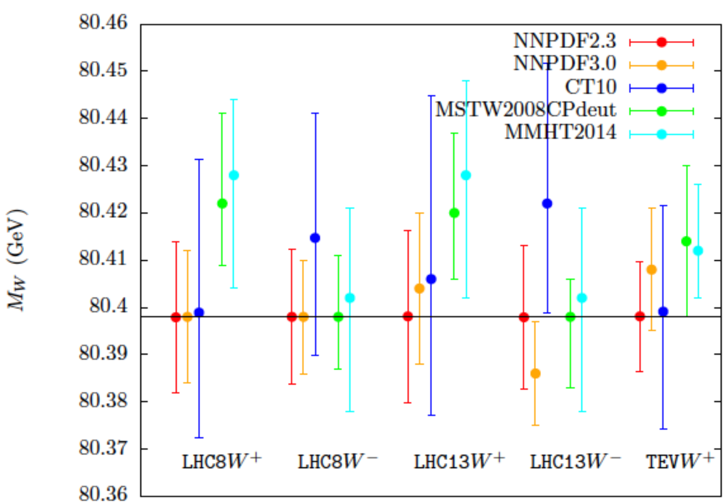
DYqT resummed predictions for the ratio of W/Z normalized q_T spectra. Correlated perturbative scale variation band.

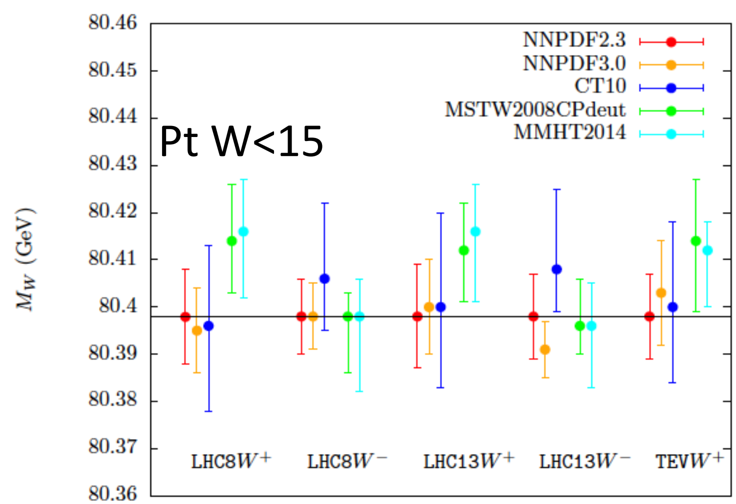
Phase space selection and PDF

- W Analysis phase space (large η lepton and low ptW) important to limit the PDF uncertainty on W mass (Vicini et al. arXiv:1501.05587)

CT10, MSTW2008CPdeut, NNPDF2.3

	no $p_\perp^W$ cut		$p_\perp^W < 15$ GeV	
	δ_{PDF} (MeV)	Δ_{sets} (MeV)	δ_{PDF} (MeV)	Δ_{sets} (MeV)
Tevatron 1.96 TeV	27	16	21	15
LHC 8 TeV W^+	33	26	24	18
W^-	29	16	18	8
LHC 13 TeV W^+	34	22	20	14
W^-	34	24	18	12





W-like – correlations in W-like

Events in the various w-like variables statistically correlated

Table 1: Correlation between the W-like fitting variables.

Variable	1	2	3
1. Lepton transverse momentum (p_T)	1.00		
2. Transverse mass (m_T)	0.67	1.00	
3. Missing transverse energy ($\not{E}_T$)	0.34	0.70	1.00

We have 50% of common events between the W-like Pos dataset and W-like Neg dataset.

Towards the W mass @ LHC

- Indicative selection:
  - ATLAS : lepton p_T>30 GeV, MET>30 GeV, m_T>60 GeV, u<30 GeV
  - CMS : 30<lepton p_T<55 GeV, 30<MET<55 GeV, 60<m_T <100 GeV, u<15 GeV